Advances in Machinery, Materials Science and Engineering Application X
M. Giorgetti et al. (Eds.)


doi:10.3233/ATDE240661

# Modelling the Flexural and Shear Behavior of Clay Based-Concrete Bilayer Beams Externally Retrofitted with Jacketed FRP Composites

Souad Ait TALEB [a,1], Abdelmadjid Si SALEM [b], Chafika Ali AHMED [a], Fatma TAOUCHE-KHELOUI [a] and Kamal Ait TAHAR [c]

[a] *Laboratory L2MSGC, Faculty of Construction Engineering, University Mouloud Mammeri of Tizi Ouzou, 15000 Tizi-ouzou, Algeria*

[b] *Civil Engineering Department, Faculty of Construction Engineering, University Mouloud Mammeri of Tizi Ouzou, 15000 Tizi-ouzou, Algeria*

[c] *Mohand Oulhadj University of Bouira, 010000, Bouira, Algeria*

**Abstract.** In order to reduce the Portland cement usage in concrete manufacturing several eco-friendly mix design has been proposed in literature, through the recourse to bio-natural products. Such technologies aim to reduce the global warming and the CO2 emission during cement manufacture. In this respect, bilayer-composite beams prepared with ordinary and clay-based concrete externally reinforced with flexural and shear GFRP-Jacket were designed and simulated in the present work. Indeed, nonlinear finite element simulations were established to evaluate the four-point bending and shear features of the suggested all composited beams. Accordingly, the novelty of this study is to propose and to validate nonlinear models (NLFEM) able to model the material behavior of concrete and clay based-concrete through an elastic-plastic damage model and anisotropic model for the constitutive behavior modelling of composite laminates. The accentuated numerical results in terms of local and global behavior are correlated with a high agreement to experimental ones.

**Keywords.** Bilayer-composite beams, FRP jacketing, clay-based concrete, nonlinear simulations, shear performances.

## 1. Introduction

In order to manufacture novel environmentally based-construction and building materials with lowest effectiveness of rapidly depleting natural resources, the use of bio-based and bio-natural materials is currently considered as an attractive solution [1-3]. Such technologies aim to preserve the natural resource and to avoid the global warming, and the CO2 emissions caused by cement production. In this respect, ZHANG et al. [4] introduced a new aspect to recycle construction waste soils to substitute fly ash in the production of eco-friendly low-carbon concrete. In addition,

[1] Souad Ait TALEB, Corresponding Author, Laboratory L2MSGC, Faculty of Construction Engineering, University Mouloud Mammeri of Tizi Ouzou, 15000 Tizi-ouzou, Algeria; E-mail: souad.ait-taleb@ummto.dz.

Zhang et al. [5] have confirmed that the incorporation of fly ash and silica fume within the concrete mixtures allowed to improve fluidity and strength. Besides, to cope with the mechanical performances decreasing caused by cement substitution, the use of the external fiber reinforced polymer (FRP) bonding as a reinforcement ensuring an increment of strength and ductility has experienced significant progress in the mechanical engineering applications as an alternative to steel plates [6-8].

Moreover, starting from a topical approach, bilayer-composite beams were introduced by Ait Taleb, et al [9]. The authors have introduced a new way to reduce the Portland cement amounts, known for his exhaustive cost in the implementation of the ordinary concrete through a new strengthened functionally graded beams. It is to replace the ordinary tensile cement based-concrete by a clay based-modified one adjusted with a lime slag inclusion conferring to the replaced quantity. In order to achieve an advanced mechanical efficiency of this innovative bilayer-graded beam externally bonded with continuous GFR-jacket, an experimental investigation based on classical experiments model has been carried out using mechanical behavior study of structures component under four-points bending test as used by [10-13].

Indeed, our contribution in this study is to propose a validate nonlinear finite element models (NLFEM), which take into consideration the material behavior of concrete and clay-based concrete beam under four-point bending through an elastic-plastic damage model and an elastic orthotropic model for the constitutive behavior modelling of FRP reinforcement. The advocated simulation procedure provides a results complement to the experimental and analytical works carried out by Ait Taleb, et al [9]. Definitely, the numerical investigation may calculate with a high accuracy the bending behavior of the studied beam system. The emphasized simulation outcomes in terms of bearing capacity and damage evolution were compared with a satisfactory agreement to the experimental ones, using qualitative and quantitative confrontation. Results discussion shows clearly the improvement in terms of mechanical performances compared to the bilayers-beam with ordinary concrete and the transition from a fragile failure to a more flexible one.

## 2. Nonlinear Finite Element Analysis

In accordance to laboratory settings, the geometric conditions of the FRP externally reinforced bilayer-composite concrete/Modified concrete beam under increasing four-point bending loads was established as shown in figure 1, which depicts the 3D view as well as the mid-span section of the proposed bilayer composite beam. Finite element modelling combined with a parametric study are established to focus the bearing capacity and the quasi-static four-point bending response of the designed beams. The total span of the beam was 1100 mm, while the beam's thickness and width are 160 mm and 80 mm respectively. The beams were composited of a clay based based-concrete in the bottom tensile zone, and cement Portland based-concrete on the top compressive zone. An external reinforcement was applied on the beam in order to improve flexural and shear features. The used FRP jacket was shaped to respond to economic concern in which high FRP volume ratio was used around of the support for which the acting shear load achieve ultimate value. The FRP amount is decreased according to a parabolic shape until the composite beam mid-span.

## *2.1. Materials Modelling*

Four concrete configurations were modeled namely: cement Portland concrete (C) and clay based-modified concrete with 16, 32 and 64 % of clay addition (CBC-16%, 32% and 64%). In addition, the FRP jacket was modelled using Tsai-Wu rupture criterion for elastic laminate, as used by [6, 14, 15]. The concrete damaged plasticity (CDP) model integrated in ABAQUS 2014 [16] was used to simulate the brittle behavior of concrete. The CDP developed by Lubliner et al. [17] was largely used to simulate FRP concrete structures [8, 18, 19]. The CDP allows to simulate with a high precision concrete members submitted to various static and dynamic loading types as it is based on a combining between plasticity and damage theory. Table 1 provides the main CDP parameter to be introduced in the FEM software to simulate the concrete and clay based-concrete under multiaxial loading.

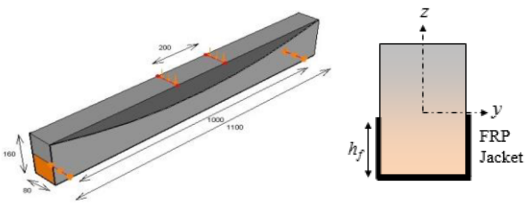



**Figure 1.** Simulated composite beam under quasi-static four-point bending.

**Table 1.** Multiaxial CDP model parameters [6, 8, 14].

| Proprieties | Concrete (C) | CBC-16% | CBC-32% | CBC-64 % |
|---|---|---|---|---|
| Dilatation Angle (°) | 32 | 30 | 26 | 24 |
| 28-day compressive stress (Mpa) | 30.5 | 27.3 | 24.4 | 15.1 |
| Yield stress on compression (Mpa) | 9.4 | 8.1 | 7.2 | 4.3 |
| Yield stress on tension (Mpa) | 2.4 | 2.23 | 2.01 | 1.51 |
| Poisson's ratio | 0.2 | 0.19 | 0.19 | 0.19 |
| Biaxial/uniaxial compressive load ratio | 1.16 | 1.16 | 1.16 | 1.16 |
| Parameter of the flow potential | 0.1 | 0.1 | 0.1 | 0.1 |
| Young Modulus (Mpa) | 32904 | 28453 | 23453 | 17954 |

The elastic behavior for 2D plan stresses was modelled by introducing the stiffness constants summarized in table 2. $E_1$ and $E_2$ are receptively FRP Modulus in the longitudinal and transverse directions. While, $\upsilon_{12}$ and $\upsilon_{13}$ are the in-plane corresponding FRP Poisson’s rations. $G_{12}$ is the shear modulus. The ultimate tensile strength of the GFRP was about 250 Mpa.

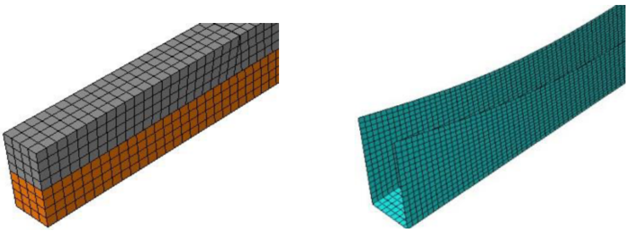
**Table 2.** FRP Lamina model parameters [20].

| $E_1$ (Mpa) | $E_2$ (Mpa) | $\upsilon_{12}$ | $\upsilon_{13}$ | $G_{12}$ (Mpa) |
|---|---|---|---|---|
| 72000 | 13600 | 0.31 | 0.33 | 4700 |

## *2.2. Finite Element Models*

According to the geometric features of the current FRP strengthened composite based-beams, a mesh stability analyses was established. A 3D hexahedral FEM with a LAGRANGIAN formulation are used to mesh the solid elements of concrete and clay-based concrete as shown in figure 2a. The GFRP-jacket is meshed using 2D quadratic finite elements model as shown in figure 2b. The solid beam FEM are constrained with the FRP shell ones using frictionless approaches assuming no bond-slip between all considered beam components. The mesh stability provides that the FEM mesh size are 2 cm and 1 cm for solid concrete and shell FRP respectively.

The simply-supports were modelled using analytical rigid shell combined to rigid body interaction to ensure a homogenized boundaries reparation. The distance between the supports was *1000 mm*. An imposed monotonic quasi-static four-point load was modelled using smooth step of the dynamic explicit, while verifying the kinetic and potential energies to ensure imposed static loading. *200 mm* spaced the acted four-point flexural forces.



a) b)

**Figure 2.** Finite element models adopted in the simulations: a) 3D Solid FEM; 2D Shell FEM.

The advocated nonlinear FEM models for the bending behavior of ordinary concrete (C) and clay based-modified concretes (CPC) are susceptible to predict the tensile and compressive damages which reflect the cracks initiating and propagating under incremental loading. More detailed explanation about the material, geometric characteristics and loading acquisition are reported in [7, 8]. Three configuration of beams were simulated according to clay addition namely: 16, 32 and 64% referred to as (GB). In terms of reinforcement type, FRP jacket layouts were considered and referend to as: (GBJ). In addition, concrete beams were simulated as control specimens and referred to as (CB).

## 3. Results and Discussions

A comparative approach was carried out on the different specimens in terms of global behavior i.e. the comparison of the capacity curves according to the cement Portland replacement with clay. This is allowing us to highlight the contribution of the bilayer-graded beams externally jacketed in terms of flexural capacity and ductility compared to equivalent plain concrete structures based on ordinary Portland cement.

Table 3 recapitulates the predicted FEM values in comparison with the average experimental ones obtained from three equal samples. The outcomes analysis indicates obviously the enhancement of the flexural strength and deflection of the bilayer beams externally jacketed compared to the control beams. The bending capacity of the GBJ with 16% substitution of Portland cement obtained by the experimental investigation is 36.76 KN, with a corresponding vertical displacement of 6.91 mm, for the other two configurations namely 32% and 64%, the ultimate loads corresponding is 25.73 and 17.21kN respectively. The flexural capacity very decreases considerably according to the cement substitution. This capacities decreasing is due to the micro-cracks concentration on the FRP-concrete interface, which producing a Jacket peeling off.

**Table 3.** Present FEM outcomes vs. average experiment values.

| Clay addition (%) | Specimens designation | FRP reinforcement | First crack load (N) | | Ultimate Capacity (N) | |
|---|---|---|---|---|---|---|
| | | | *Test[7]* | *Present FEM* | *Test [7]* | *Present FEM* |
| 0 | CB | / | 6450 | 6540 | 8750 | 9520 |
| 16 | GB | / | 6320 | 7130 | 8110 | 9140 |
| | GBJ | Jacket | 26310 | 23880 | 36760 | 34780 |
| 32 | GB | / | 4790 | 6120 | 6530 | 8320 |
| | GBJ | Jacket | 17180 | 16430 | 25730 | 24190 |
| 64 | GB | / | 2340 | 1950 | 3870 | 4210 |
| | GBJ | Jacket | 13450 | 12540 | 17210 | 19080 |

Figure 3 shows the tensile damages maps of the present FEM compared to the real failure modes of bilayer graded beams. Based on the morphological comparison, the predicted damages link with a good correlation with the experimental cracks. An acceptable agreement was recorded between the predicted NLFEA values and the test ones. The simulated maximum loads were marginally greater than the test forces which is caused by the first deflection of the externally jacketed FG beams.

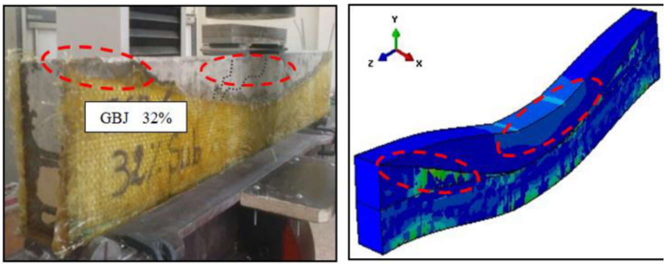



**Figure 3.** Test failure mode vs. tensile damages of the beams designed with 32 % of clay addition.

## 4. Conclusion

This paper aims to advocate nonlinear models susceptible to predict the total bending response of bilayer-composite beams designed to reduce the usage of ordinary Portland cement and to improve the knowledge of natural-geological materials though a novel beam strengthened with external bonded GFRP sheets. This s aims in one hand to increase the flexural stiffness and strength, and in the other hand to prevent sudden failure under excessive loading.

The simulation results of the analysis carried out on reinforced beams under flexural loading confronted to experimental ones show clearly the improvement in terms of mechanical performances compared to the bilayers-beam with ordinary concrete and the passage from a brittle failure mechanism to a ductile failure mode. The analysis of various considered substitution configurations in order to optimize the modified concrete formulation shows that the graded beams with 64% substitution of Portland cement presents a ductile behavior and of high deformation energy compared to the control beam.

Finally, a good agreement was recorded between the predicted NLFEA values/maps and the test ones. However, the simulated maximum loads were marginally greater than the test forces which is caused by the first deflection of the externally FRP jacketed which was overestimated in the present numerical study.

## References


[1] Pratap R, Raja K and Jadda K. Durability assessment of fly ash, GGBS, and silica fume based geopolymer concrete with recycled aggregates against acid and sulfate attack. J. Build. Eng. 2024; 82: 108354.

[2] Alma'aitah M and Ghiassi B. Development of cost-effective low carbon hybrid textile reinforced concrete for structural or repair applications. Constr. Build. Mater. 2022; 341.

[3] Ashwini B. Comparison of mechanical properties of concrete incorporated with Multiwalled Carbon nanotube and partial replacement of cement with flyash. Mater. Today Proc. 2023.

[4] Zhang L, Chen Z, Chen R, Zhu S, Lin J and Tai P. Compressive strength of fly ash based geopolymer utilizing waste completely decomposed granite. Case Stud. Constr. Mater. 2023; 19: e02667.

[5] Zhang H, Cao L, Duan Y, Tang Z, Hu F and Chen Z. Case Studies in construction materials high-flowable and high-performance steel fiber reinforced concrete adapted by fly ash and silica fume. Case Stud. Constr. Mater. 2024: e02796,

[6] Djenad S, Ait Taleb S, and Si Salem A. Finite element modeling of partially-confined concrete and RC columns with embedded hexagonal-FRP strips under axial and horizontal loading. Structures. 2023; 54: 369–385.

[7] Ait Taleb S, Si Salem A and Ait Tahar K. Behaviour of a new graded beam reinforced with externally bonded composite sheets: theoretical and experimental studies, Eur. J. Environ. Civ. Eng. 2017; 21(9): 1171–1185,

[8] Taleb SA, Salem AS and Tahar KA. Bending and shear behavior of a composite beam strengthened and double-confined with FRP-Jacket. Procedia Eng. 2015; 114:165–172.

[9] Ali Ahmed C, Si Salem A, Ait Taleb S and Ait Tahar K. Experimental behavior and reliability of predamaged concrete columns externally repaired with FRP spiral strips under axial compression. World J. Eng. 2022.

[10] Bouzeboudja F and Salem AS. Experimental investigation on flexural behavior of textile-reinforced concrete: effect of reinforcement and dune sand addition. WJE. 2023. doi: 10.1108/WJE-05-2023-0139.

[11] Ait Taleb S, Si Salem A and Ait Tahar K. Experimental and theoretical modeling coupled to a reliability approach for flexural failure prediction in hybrid composite beams. Asian J. Civ. Eng. 2020; 21(3): 495–504,

[12] Medjmadj S, Si Salem A and Ait Taleb S. Experimental behavior of plaster/cork functionally graded core sandwich panels with polymer skins. Constr. Build. Mater. 2022; 344: 128257.

[13] Salem AS, Taleb SA, and Tahar KA. Experimental and statistical investigation of a new concrete-composite beam with encased polymer tube wrapped by FRP. Front. Struct. Civ. Eng. 2015; 9(2): 154–162.

[14] Djenad S, Ait S, Si A and Bouzidi MA. NLFEA based design optimization of GFRP strips in partially confined concrete. Procedia Struct. Integr. 2022; 37: 321–329.

[15] Salem AS, Taleb SA and Tahar KA. A finite element approach for predicting the flexural response of light weight frp-concrete beams under cyclic loading. Lect. Notes Mech. Eng. 2017; p. 355–363.

[16] ABAQUS/standard user's manual, version 2014. United States: Dassault Systèmes Simulia Corp; 2014.

[17] Lubliner J, Oliver J, Oller S and Oñate E. A plastic-damage model for concrete. Int. J. Solids Struct. 1989; 25(3): 299–326.

[18] Taleb SA, Medjmadj S and Salem AS. Modeling the nonlinear behavior of predamaged reinforced concrete beams retrofitted with bonded and jacketed frp sheets. Eurasia Proc. Sci. Technol. Eng. Math. 2022; 21: 288–294.

[19] Salem AS, Taleb SA and Tahar KA. Static and dynamic behavior of composite concrete-based beams with embedded polymer/FRP components. Procedia Eng. 2015; 114: 173–180.

[20] Salem AS, Taleb SA and Tahar KA. Experimental and statistical investigation of a new concrete-composite beam with encased polymer tube wrapped by FRP. Front. Struct. Civ. Eng. 2015; 9(2): 154–162.